Following the completion of the draw/coating process, the fiber is measured for its optical performance, a resistance measurement for the carbon coating is taken and coating geometry measurements are made at a test bench. Bandwidth measurements are made at three wavelengths, loss measurements are made at approximately 6 wavelengths including 1380 nm for the water peak. Numerical Aperture (NA) is measured at an unspecified wavelength. The resistance measurement is used for screening the quality of the carbon coating. Geometry measurements include: core and cladding diameter, core and cladding noncircularity, clad/core concentricity, polyimide coating diameter, and coating concentricity.

When non-conforming sections of fiber need to be removed from the reel, the fiber is respooled under a de-ionizing fan used to remove charge. Sub-spools of a single draw lot are assigned the same draw lot number and a unique letter identifier suffix for the spool.

The carbon and polyimide coating processes were reviewed during the on-site visit and were discussed several times over the period of the investigation to understand how they may contribute to or support the root cause of failure. Table 7 lists the concerns investigated and the corresponding findings.

Table 7 Coating Issues & Findings

Issue	**Finding**
Is there an opportunity for debris to fall into the coating cups from the carbon application station	An exhaust system is used below the reactor to prevent this.
The temperature of the carbon application process could be re-melting the glass or vaporizing contamination in the glass	The process actually requires cooling of the glass as it exits the draw iris.
Can the polyimide melt during FEP extrusion?	No because polyimide does not melt.
Can the in-line diameter sensors detect the depressions and bubbles in the polyimide, which tend to be associated with the “rocket engine” defects?	The laser micrometer system has a range from 0.067-2mm (67 microns-2000 microns) a resolution of 0.0001mm (.1 microns) a repeatability of ±.0.0001mm and a linearity of ±0.001mm. This equipment is not suitable for finding 10 micron sized features.

5.0 INSPECTION TECHNIQUES AND FAILURE ANALYSES

5.1 Optical Inspection

Comparisons of several different measurement methods were accomplished over the course of the investigation. Attenuation meters, optical fault finders (OFF) and optical time domain reflectometers (OTDR) were used as part of the harness acceptance procedure and during failure analysis. A ray tracing analysis was performed by Boeing, which showed that the size, shape and typical location of the defect made it somewhat invisible to an OTDR. “Rocket engine” defects, which did not reach sufficiently deeply into the core, would be even more difficult to detect with a meter measuring transmitted or returned power.

Attenuation measurements were made with a Model CP-1107 Optical Power Tester manufactured by RIFOCS (1300 nm wavelength, +3 to –80 dBm dynamic range) after harness assembly and during their integration into the US Lab module at KSC. A limit of 1.5 dB per link was used by Boeing though most achieved closer to 0.5 dB, which is associated with connector loss. Link lengths on the US Lab are between 10 and 60 ft [ref-5]. After installation, a system level acceptance was imposed based on successful operation of the data bus. The operational margin afforded by the receivers is between 11.5 dB and 26 dB depending on the type of system (audio or visual) it is part of. Changes in link attenuation associated with degrading fiber may not be discernable using a system test.

Optical fault finders (OFF), which launch < 1mW of red light into the fiber core, were also used to find breaks. The FEP and Teflon™ strength members are transparent to this wavelength and revealed a glowing spot where light was escaping from the fiber through a break or other defect that reached into the core. Research has shown that operators must be dark adapted (@ 20 minutes in a completely darkened room) to effectively use OFF’s. Experiments at GSFC showed that several of the defects believed to be “rocket engine” defects, were not found with an OFF until the screen was done following dark adaptation. By using a green laser (< 1 mW, 532 nm, class II), visual sensitivity is raised by a factor of 10, further improving the efficiency of the screening method. Increasing the power of the laser used will also improve the screen, which was verified using a 20 mW HeNe laser. Screening with the 20 mW laser did not damage the fiber. A maximum power for inspecting this fiber, in this manner, was not investigated.

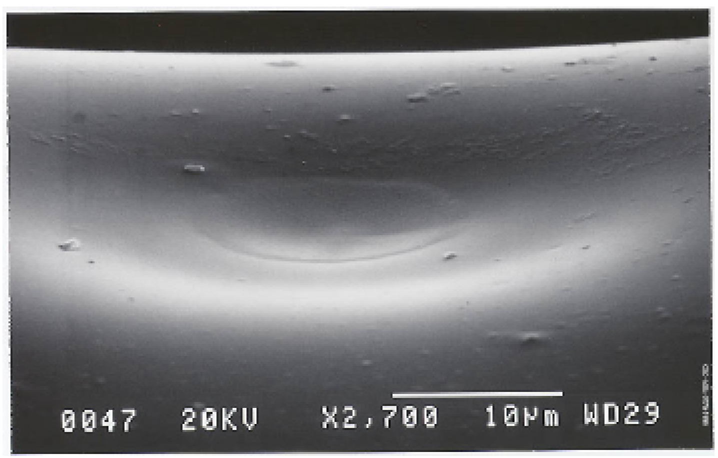
Optical Time Domain Reflectometers (OTDR) were also used to estimate attenuation and especially to locate the defects. Several different models were used with varying sensitivity due to the type of signal launch each used. The models used were the Tektronics TFP2 FiberMaster and the Opto Electronics Inc. OFM20 and OFM130. BICC uses a Tektronix TFP2 FiberMaster and a GNNettest CMA 4000 at 1300 nm [ref-6]. The GNNettest was not evaluated with a length of cable with known “rocket engine” defects. The OFM130 was determined to the best of the three evaluated because it has a zero meter dead zone and a 0.1 μsec pulse [ref 7]. The OFM130 was able to identify the location of more defects than the FiberMaster. Following screening with an OFF, which found yet more defect sites, the OFM130 was applied. By increasing the OFM130’s gain to close to its maximum level and scanning the cable at the positions identified by the OFF screening, all of the defects were found.

It is clearly more labor intensive to locate the “dim” spots using only an OTDR. All three OTDR models were also found to show ghost pulses when used with concatenated harnesses. Time and the availability of experienced OTDR operators are required if the OTDR is to be depended on for a screening method for these defects. A Brillouin OTDR was suggested for use but would not be suitable here because its operational mode does not allow the sensitivity required.

5.2 DPA Results

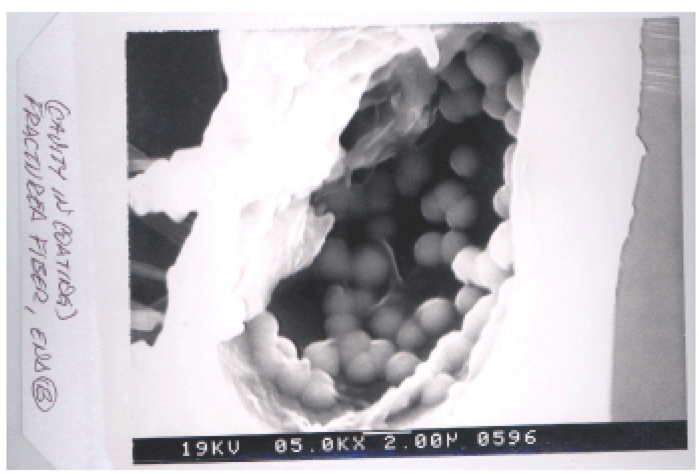
Destructive Physical Analyses (DPA) were done when multiple defects were being found following periods where no stress was induced on the cable (glows appearing after the cable sat on the bench overnight). Most of the early DPA’s were done on fiber ends and glow spots on the fiber that had not broken into two pieces at a defect site. When a glow was found in the cable, the affected section was cut from the spool or harness and the fiber was removed from the cable. Often, the fiber broke during this removal operation. When it didn’t, the fiber was sometimes bent until a complete break occurred. In either case, the break always occurred at the defect site. The end face images were not mirrors of each other indicating loss of material during the break. As the investigation progressed intact fiber with defects were imaged.

Figure 1 above is one of the very first images of a rocket engine defect made available by Boeing-HB. Subsequent DPA’s found other important features, which ultimately led to the HF etching theory. These are shown in Figures 5 through 10.



Courtesy of The Boeing Corporation

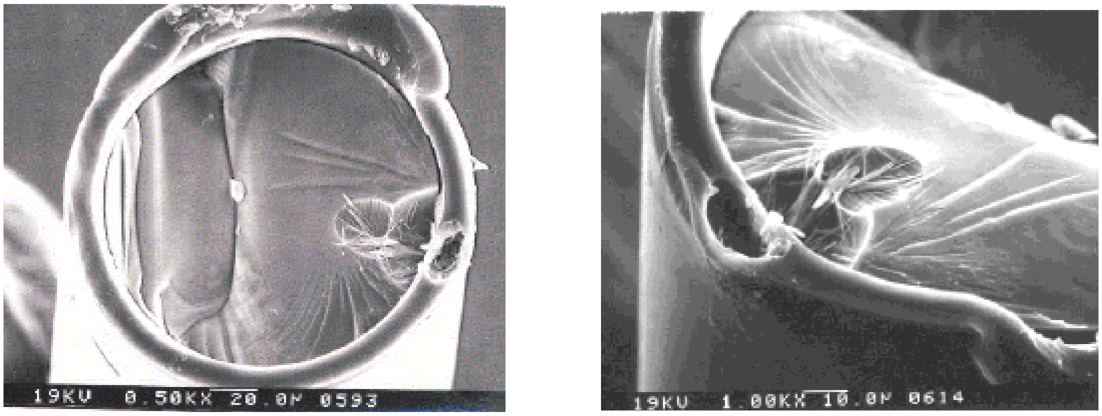
Figure 5 Sink in the Polyimide Coating



Courtesy of The Boeing Corporation

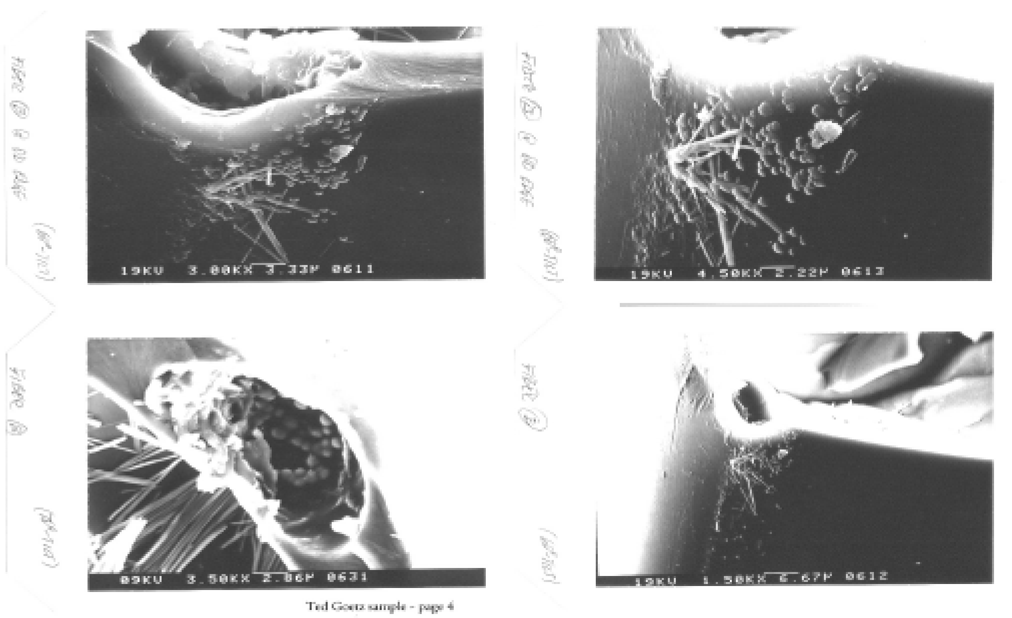
Figure 6 SiO2 Balls in Polyimide Void

a. b.



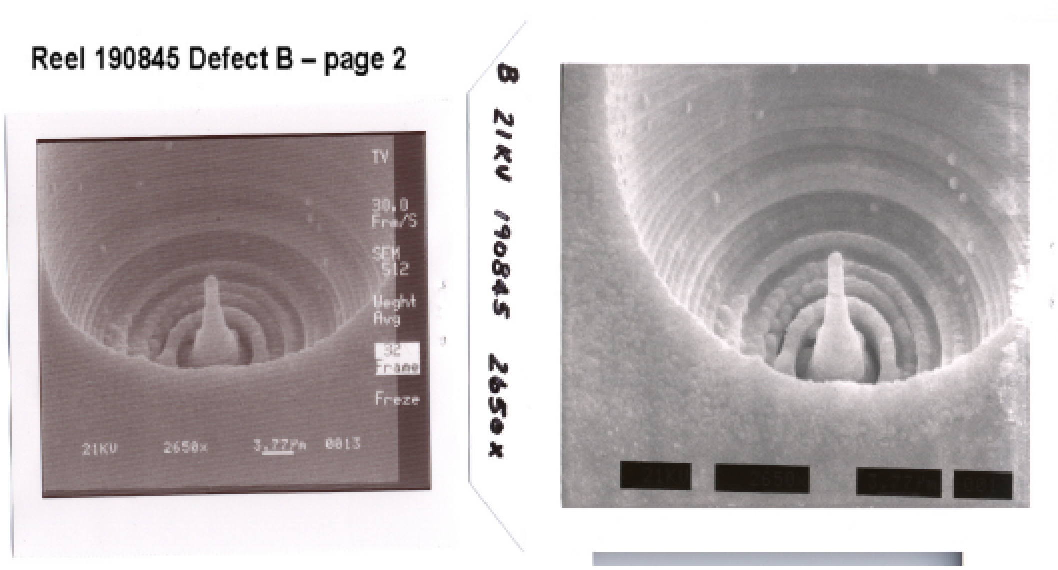
Courtesy of The Boeing Corporation *Courtesy of The Boeing Corporation*

Figure 7 GeO2 Crystals in Etch Pit



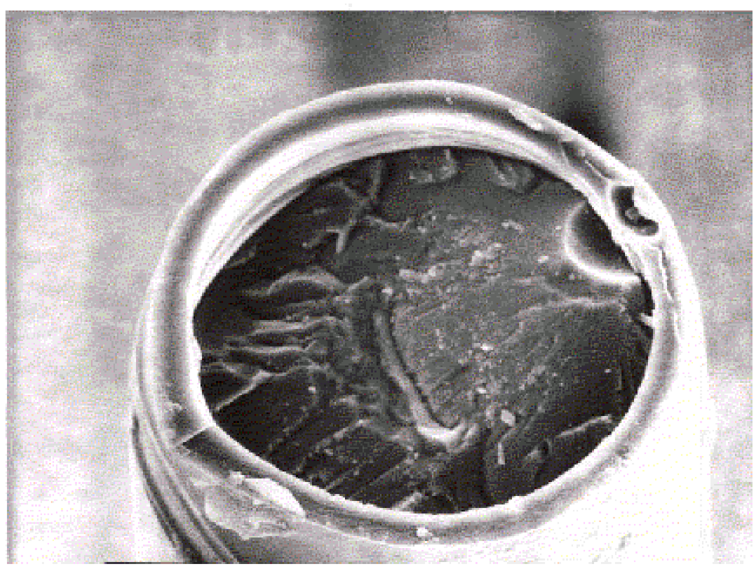
Courtesy of The Boeing Corporation

Figure 8 GeO2 and SiO2 Debris on Outside of Coating



Courtesy of The Boeing Corporation

Figure 9 Si-spire in Deep Etch Pit



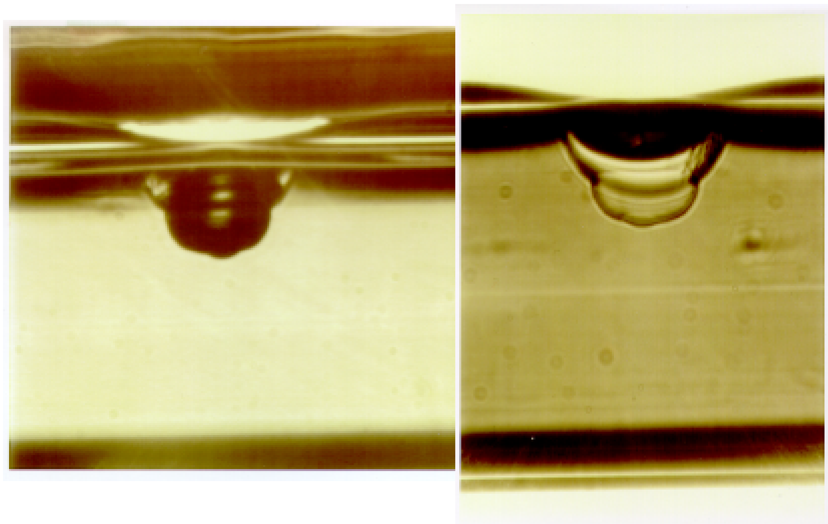
Courtesy of The Boeing Corporation

Figure 10 Characteristic Void in Polyimide Above Shallow Etch Pit

These figures were all produced with a scanning electron microscope. EDX was used to determine the composition of the glass to determine the presence of contamination and to identify the composition of the spheres and crystals found in Figures 6 and 7. Polarized light was used to confirm that the "shards" were indeed crystalline. Optical microscope images are also available but are more difficult to interpret independently.

The use of index matching oil and backlighting during imaging was found to greatly enhance the optical microscope images. After submersion of an intact piece of fiber in index matching oil and having left the sample overnight, the oil was found to have filled the "rocket engine" void (Figure 11a and 11b). This indicated that the surface of the "rocket engine" defect was exposed to ambient atmosphere.

a. b.

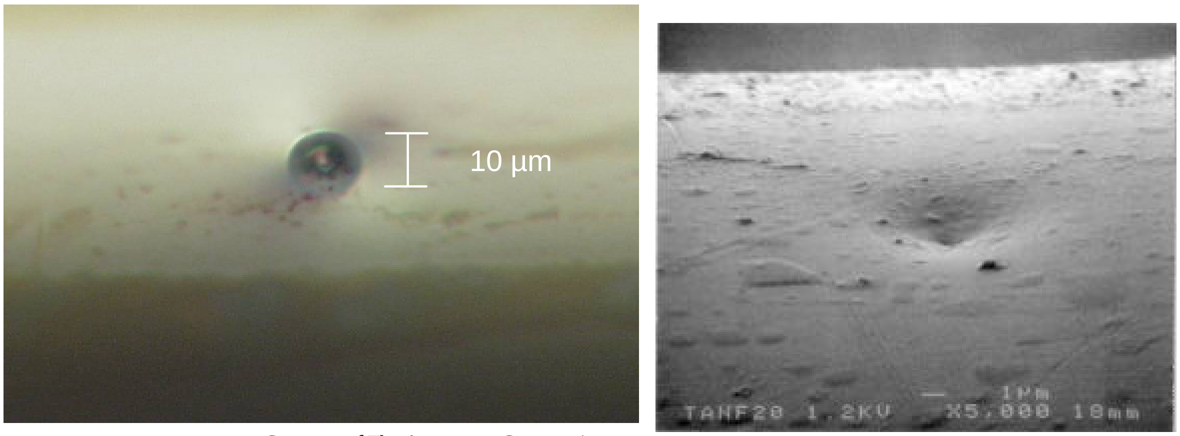


Courtesy of NASA GSFC

Figure 11 Defect Inspection Using Index Matching Oil

Optical inspections were also performed on a section of fiber with no "glow" spots which was taken from a cable with many "glow" spots in other locations. This review showed that the "rocket engine" was not the only observable defect but that many concave "sinks" were found in the polyimide and were believed to be bubbles or indicative of smaller "rocket engine" defects which did not reach beyond the cladding into the core of the fiber. The frequency of these additional defects was one every three to four millimeters (4 to 6/inch).

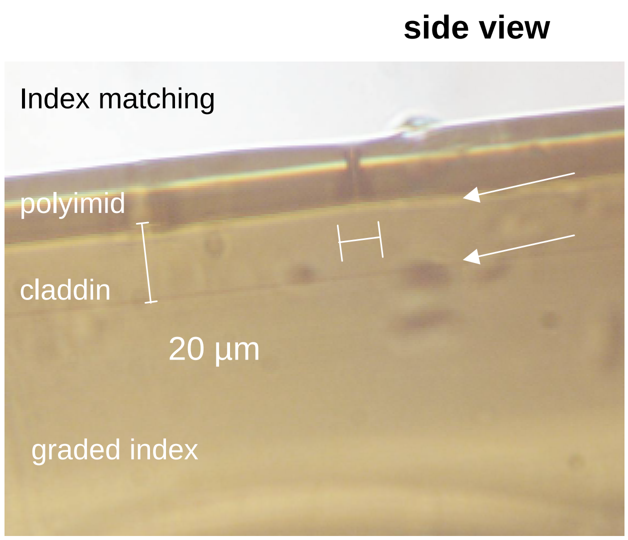
Optical inspection was used to examine the polyimide surface of fiber containing "glows". Features were found resembling depressions and buried bubbles (Figures 5-8, 10, and 12). Field emission scanning electron microscope (FE-SEM) inspections were also performed on 6" samples from two lots of fiber which had never been cabled by BICC (Figure 13) [ref 8]. The samples were from reels CD0588XD and CD0384XB. Though both lots were found to weaken due to the cabling processes, the CD0588XD fiber was found to be more dramatically weakened than the CD0384XB (see Section 7.0).   Sixteen features were found in the polyimide in the "588" sample and one was found in the polyimide in the "384" sample (four more features were found in an additional sample of "588" fiber). An hour glass-like shape was found to be very common among the bubbles observed, as is shown in Figure 13.



Courtesy of The Aerospace Corporation *Courtesy of The Aerospace Corporation*

a. OPTICAL *b. FM-SEM, 60° to Normal to Surface*

Figure 12 Depressions and Bubble in Polyimide Coating in Fiber CD0588XD



Courtesy of The Aerospace Corporation

Figure 13 Hourglass Shape of Bubble and Polyimide